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WITH A FREELY EXPANDING ELECTRON BEAM

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TIME RESOLVED EMITTANCE MEASUREMENTS WITH A FREELY EXPANDING ELECTRON BEAM*

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Abstract

Time resolved rms emittance measurements have been made on the ETA by allowing the electron beam to freely expand into a magnetic field free vacuum region while measuring beam size versus time with x-ray probes at three axial positions. The beam is not required to be at a waist. Temporal resolution is limited only by the beam size measurement technique, which for the x-ray probe technique is subnanosecond. The analysis consists of matching parameters of the beam envelope equation with measured radii. Space charge effects were ignored since they were small for this experiment. They can be easily included but the resulting envelope equation must be solved numerically. Emittance measurements of the wire zone conditioned electron beam will be given.

Introduction

Temporally resolved beam emittance measurements have been made on the Experimental Test Accelerator (ETA) with an x-ray probe beam radius measuring technique. Although not yet used, this technique is also applicable to the Advanced Test Accelerator (ATA). The ETA and ATA are induction linacs. The ETA produces up to a 30 ns FWHM 4.5 MeV electron beam at a 1 Hz rate.¹ Transverse beam motion typical of this type of accelerator has been controlled by phase mixed damping with an electrostatically charged wire.² The phase mixed damping, however, transfers transverse beam motion into increased emittance. Therefore it was desirable to measure the emittance of the beam after passing through the wire zone. An emittance measurement with pepper pot and optical beam size measurements with phosphorescent foils was not practical because of the high beam emittance and current. Beam size measurements of the freely expanding beam in a vacuum were instead made with x-ray probe techniques.³ This technique consists of scanning a high z target through the beam as the target position and the resulting x-ray signals are recorded. By accumulation of the x-ray signals at many random target positions it is possible to reconstruct a beam size and profile with the time resolution of the x-ray detector. This technique does require that jitter in beam profile and position be minimal.

Theory

The paraxial envelope equation for a round beam in vacuum is given by⁴

$$r \frac{d^2 r}{dz^2} + k^2 r^2 = 2 \frac{I_b}{I_A (\beta\gamma)^2} + \epsilon^2 / r^2, \quad (1)$$

where I_b is the beam current, r and ϵ the rms beam radius and emittance, respectively, I_A the Alfvén current = $4\pi \epsilon_0 mc^3 \beta\gamma/e = 17 \beta\gamma$ kA, and the solenoidal focusing $k = eB_z/2\gamma mc \beta c$. Since the experiment was done in a field-free region k is zero. Also, since for any time in the pulse the beam current is constant we define the constant $C = 2 I_b / I_A (\beta\gamma)^2$. After multiplying by r' the first integration of Eq. (1) can be performed.

$$r'^2 = r_0'^2 + 2 C \ln \left(\frac{r}{r_0} \right) + \epsilon^2 \left(\frac{1}{r_0^2} - \frac{1}{r^2} \right) \quad (2)$$

For non-zero space charge, i.e., for C not small Eq. (2) must be evaluated numerically. This can be done by minimizing about initial estimates for r_0 and ϵ . However, to simplify the analysis, I consider space charge effects to be small and let $C = 0$. (For the data presented later this assumption is not justified except at the front and back of the pulse where the beam current is small.) Thus, Eq. (2) can be integrated to give

$$r^2 = r_0^2 + \Lambda^2 (z - z_0)^2 + 2 r_0 r_0' (z - z_0) \quad (3)$$

where

$$\Lambda^2 \equiv r_0'^2 + \frac{\epsilon^2}{r_0^2}.$$

The unknowns are r_0 and Λ^2 . They are determined from beam size measurements at three locations.

Solving for these unknowns and defining $\Delta_i^2 \equiv r_i^2 - r_0^2$ and $s_i \equiv z_i - z_0$ gives

$$r_0'^2 = \frac{\Delta_2^2 s_1^2 - \Delta_1^2 s_2^2}{2 r_0 s_1 s_2 (s_1 - s_2)}$$

and

$$\Lambda^2 = \frac{\Delta_1^2 s_2 - \Delta_2^2 s_1}{s_1 s_2 (s_1 - s_2)}.$$

For $r_0' = 0$ Eq. (3) yields the familiar result of $r^2 = r_0^2 + (z - z_0)^2 \epsilon^2 / r_0^2$.

Thus, by measuring beam size at three z locations we have a way to determine the initial radial velocity and beam emittance.

The Experiment

The experimental setup is shown in Fig. 1. Solenoid produced B_z fields are used to transport the beam upstream of the entry foil. Downstream of the foil these fields vanish. Two types of probes were scanned through the beam to measure beam size. These were a bow probe, which consists of a stirrup-like holder and x-ray target, and a swinger probe, which has an arm that rotates a target through the beam. The bow probe was located at 3 cm, and the swinger probes 11 and 21.9 cm from the entry foil to the experimental tank. The bow probe x-ray target was a 75 mm long, 3 mm diameter tantalum wire. The swinger probe target was a 75 mm long, 4.7 mm diameter graphite rod with a 3.2 mm diameter hole filled with powdered tungsten. The x-ray signals were detected with a Hamamatsu R1194U microchannel plate photomultiplier tube. No scintillator was used and light and low energy x-rays were prevented from entering the tube with a 1.6 mm thick aluminum shield. The PM tube signal was recorded with a Tektronix 7912 transient digitizer connected to an LSI-11 microcomputer using the Tektronix SPSBASIC

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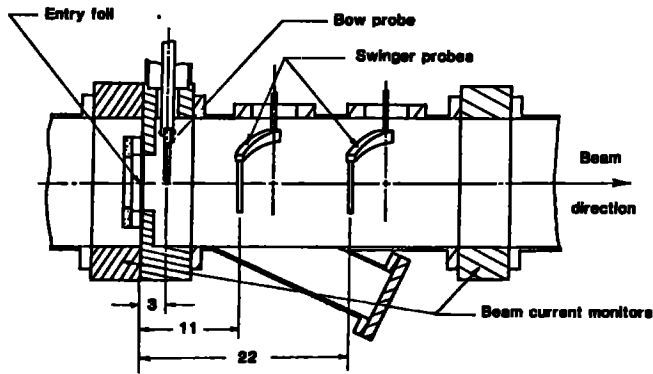


Fig. 1. Experimental layout for measuring beam size at three locations. Distances are in cm from the entry foil.

operating system. Probe positions, as recorded by position encoders, were also input to the LSI-11. Thirty-two discrete values of the signal for 256 shots were recorded during the scans.

Data and Analysis

Data from the bow probe scan at 3 cm from the entry foil is shown in Fig. 2. It has been time correlated so that each frame represents x-ray amplitude and probe position of all the shots at one time within the pulse. Peak beam current for these shots was 6 kA, and beam energy was 4.3 MeV. The curve drawn through the points is a least squares fit to a truncated bennett profile with background and arbitrary beam centroid position, $f(x) = a + b/[1 + (x - x_0)^2/x_b^2]^2$. As is apparent, the x-ray

back-ground is significant. This signal can be reduced by suitable shielding. If the beam radius is larger than the scan range, then there is some ambiguity as to how to choose the background level. For this data set it was chosen as the lower of the average of the signals at either limit of the scan.

In Fig. 3 measured beam half-amplitude radius is shown as a function of time at three axial locations. The background signal, which is proportional to the beam current, is superimposed. From this data set an emittance is determined at 4 ns intervals using Eq. (4) and multiplying the radius by a factor 1.10 to convert to an rms value. These results are shown in Fig. 4. The emittance was calculated both with and without assuming $r_0 = 0$ with very little difference between the resulting values. The beam emittance is seen to be much larger at the head of the pulse but remains relatively constant thereafter.

Discussion

Several things about the technique were learned from this experiment. First, it is best to keep the x-ray background as small as possible in order to correctly find the beam radius. Second, the scan travel should be enough larger than the largest expected beam size to allow for establishing a correct background level. Third, a profile other than a bennett profile would allow for easier determination of an rms radius. With a bennett profile the rms radius is dependent on the somewhat arbitrary choice of the edges of the profile. A gaussian profile would be a better choice but that has not yet been implemented. Fourth, a correct calculation must include the space charge effects. For this last reason the emittance shown in Fig. 4 needs to be modified for space charge effects.

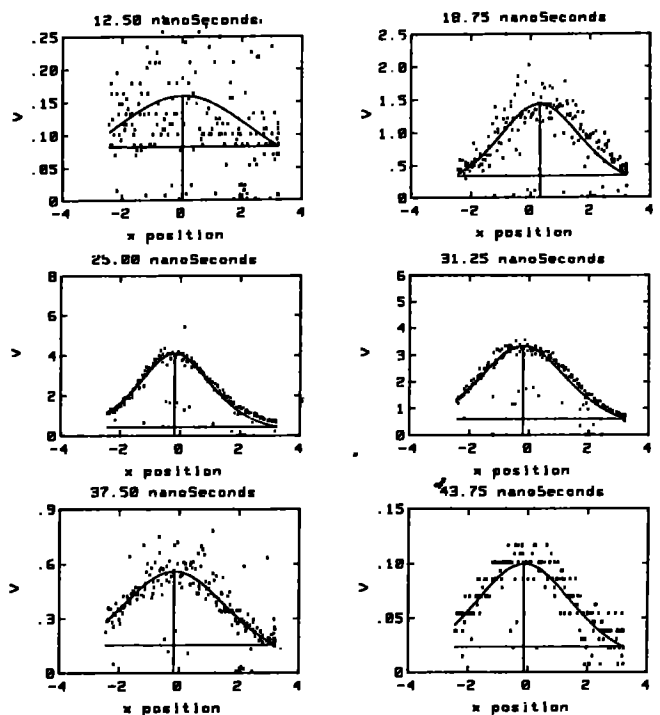


Fig. 2. X-ray amplitude versus probe position at several times in the pulse at the 3 cm location.

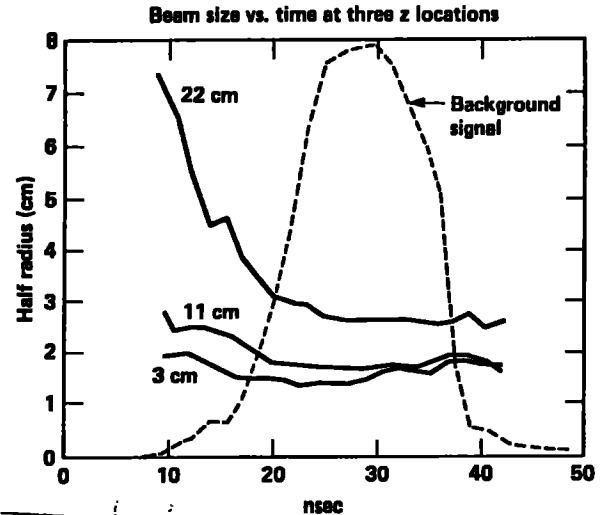


Fig. 3. Measured beam half amplitude radius versus time.

Conclusion

Temporally resolved measurements of electron beam emittance are practical with x-ray probe scanning of beam expansion in a vacuum. It does require data collection from many shots of a jitter free beam. Furthermore, some computational analysis is required. For this effort emittance values at many times throughout the pulse are obtainable.

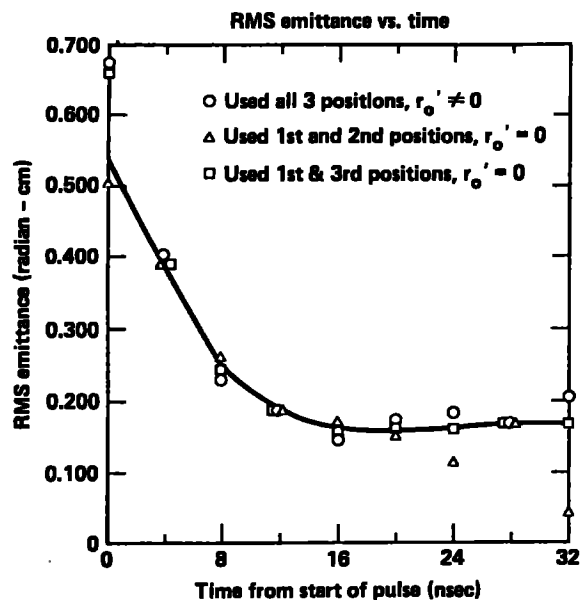


Fig. 4. Beam emittance versus time.

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